DEEP IMPACT: THE ANTICIPATED FLIGHT DATA

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Abstract. A comprehensive observational sequence using the Deep Impact (DI) spacecraft instruments (consisting of cameras with two different focal lengths and an infrared spectrometer) will yield data that will permit characterization of the nucleus and coma of comet Tempel 1, both before and after impact by the DI Impactor. Within the constraints of the mission system, the planned data return has been optimized. A subset of the most valuable data is planned for return in near-real time to ensure that the DI mission success criteria will be met even if the spacecraft should not survive the comet's closest approach. The remaining prime science data will be played back during the first day after the closest approach. The flight data set will include approach observations spanning the 60 days prior to encounter, pre-impact data to characterize the comet at high resolution just prior to impact, photos from the Impactor as it plunges toward the nucleus surface (including resolutions exceeding 1 m), sub-second time sampling of the impact event itself from the Flyby spacecraft, monitoring of the crater formation process and ejecta outflow for over 10 min after impact, observations of the interior of the fully formed crater at spatial resolutions down to a few meters, and high-phase lookback observations of the nucleus and coma for 60 h after closest approach. An inflight calibration data set to accurately characterize the instruments' performance is also planned. A ground data processing pipeline is under development at Cornell University that will efficiently convert the raw flight data files into calibrated images and spectral maps as well as produce validated archival data sets for delivery to NASA's Planetary Data System within 6 months after the Earth receipt for use by researchers world-wide.

Keywords: Deep Impact, comet, Tempel 1, data set, calibration, data processing, data archive

1. Introduction

To achieve the Deep Impact (DI) mission goal of obtaining mankind's first look inside a comet, an instrument suite has been developed that will allow us to characterize the nucleus of Tempel 1 as it exists at the time we arrive, during the cratering event caused by our Impactor, and after the crater formation is complete. The compositional and dynamical nature of the crater ejecta will be determined, and the deep interior of the nucleus will be revealed in the walls and floor of the crater we create. The nature of Tempel 1's near-nucleus dust and gas coma will also be monitored before and after the impact event to help us understand its formation, geometry,

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composition, and evolution. The Deep Impact scientific data set will provide key measurements that will allow us to better determine what comets are made of and how they change throughout their lifetime.

To achieve Deep Impact's science objectives (see papers by A'Hearn *et al.*, Thomas and Veverka, Schultz and Ernst, Richardson *et al.*, Sunshine *et al.*, and Belton *et al.*, in this volume), measurements involving visible images and infrared (IR) spectral maps are required. Hampton *et al.* (this volume) describes the instruments being flown on Deep Impact and their measurement capabilities in a companion paper. The instruments on the main Flyby spacecraft comprise a High-Resolution Instrument (HRI) with a visible imager (HRIVIS) and an infrared spectrometer channel (HRI-IR) and a Medium-Resolution Instrument with a visible imager (MRI or MRIVIS). The Impactor carries a duplicate of the MRIVIS (except without a filter wheel) called the Impactor Targeting Sensor (ITS). The design of the Deep Impact mission and a summary of its spacecraft capabilities are contained in the paper by Blume *et al.* (this volume).

The measurements required for the DI instruments must span a wide range of time scales, spatial scales, and lighting conditions to fully characterize Temple 1 and the impact event. However, the extent of the data set is limited by the practical constraints of the spacecraft and instrument capabilities. Flying close to an active comet is also not without risk, and we have tried to ensure that we return all of the absolutely essential data prior to closest approach. Numerous tradeoffs have had to be made to define what we believe is the optimum data set that can be obtained within the existing constraints.

2. Constraints Limiting Data Acquisition

One constraint on the DI data set is imposed by the rate at which images and spectra can be read out of the instruments. Low-noise instrument performance can only be achieved if detector readout rates are limited. For the DI visible cameras, a full 1024×1024-pixel frame requires 1.42 s to read out. Overhead time to open and close the shutter, transfer the image from the active portion of the CCD array into its storage region, plus instrument internal timing margins increase the minimum frame time in this mode to 1.84 s even with zero-signal integration time. Adding filter wheel steps costs another 1.1 s per step. While frame times of a few seconds are normally perfectly acceptable, there are times, such as at the instant of impact, where the maximum time sampling rate is desired, requiring frame intervals of a fraction of a second.

Other camera modes are selectable that do provide shorter frame times at the expense of frame format size and the ability to use the shutter between frames to protect against any scene saturation causing charge to bleed into the storage register. Identical frames taken in immediate succession can be obtained slightly faster than successive frames with command parameters that are not identical. Minimum frame

TABLE I
DI VIS camera minimum frame times.

Frame format	Shuttered mode (s)	Unshuttered mode (s)
512 × 512	0.74	N/A
256 × 256	0.43	0.23
128 × 128	0.31	0.11
64 × 64	N/A	0.058

intervals for successive identical frames with zero integration time and no filter steps are given in Table I. The selected integration time must be added to these values to derive the actual frame intervals.

For the IR spectrometer, a full 512 spectral × 256 spatial frame takes 2.86 s with zero-added integration time (even with zero-added integration time, signal is integrated on the detector for the minimum frame time, if the detector is read out in an interleaved mode, or half the minimum frame time in the alternating readout modes). IR subframe modes with reduced spatial coverage are available that have shorter frame intervals: 512 × 128 takes a minimum of 1.43 s, and 512 × 64 takes 0.73 s. IR spectrometer data can be returned "unbinned" as well as in the normal 2 × 2 binned modes; see the companion paper by Hampton *et al.* (this issue) for more details on IR spectrometer data binning and its effects on spatial and spectral resolution.

The DI data set is also limited by the amount of data storage memory available onboard. When the data-taking rate is low and DSN coverage is ample, this buffer memory limit is not a real constraint. However, when we wish to take a large amount of data in a very short time, the buffer memory becomes a first-order constraint on what data can be captured. The Flyby spacecraft provides an allocation of 309 MB (megabytes) of science data storage for the Flyby instruments on each of two computer strings. Data can be directed to be stored on both strings (for redundancy in case a computer fails before the memory contents can be telemetered to the Earth) or to one or the other string. The Impactor spacecraft provides only about 100 MB of science data storage; however, data are not stored for any appreciable length of time on the Impactor during the time-critical period just prior to impact, so this limitation is of no concern. The Flyby computers have an additional allocation of 31 MB of storage for Impactor data; this allocation only becomes a constraint for times when we gather Impactor data while there is no ongoing downlink, e.g., during calibration activities.

The downlink data rates to the Earth determine how long it takes to empty the onboard data buffer. Data rates vary from a low of about 20 kbps (for example, when using the low-gain antenna shortly after launch or the high-gain antenna to a 34-m DSN station after encounter) to a maximum of 200 kbps (for example, over the high-gain antenna near encounter to a 70-m DSN station). Even at the maximum downlink rate, it takes about 4.5 h to empty one 309-MB memory. Since the high-priority impact-related observations are completed in less than 20 min, these data are limited to what can be stored in the onboard buffers. During the early portion of the approach to the comet when the mission plan provides only 34-m DSN coverage, mostly for only one 8-h pass per day, we are limited by the downlink rate to acquire no more than about 1 Gb/day. This limit goes up during the later portions of approach to about 3 Gb/day for continuous 34-m DSN coverage and to about 14 Gb/day for continuous 70-m DSN coverage.

After release of the Impactor, data are transmitted at 60 kbps from the Impactor to the Flyby spacecraft over an S-band radio link. Telemetry formatting overhead uses about 25% of this rate leaving no more than about 50 kbps for science data. During the time shortly before impact, the Impactor data are sent immediately to the ground by the Flyby as soon as they are received. This approach keeps the maximum amount of Flyby storage memory available for post-impact Flyby science data and also ensures that the Impactor images are returned to the Earth well before the most risky closest approach event. The Flyby imposes its own ~25% telemetry overhead on the Impactor data. Thus, to keep up with the flow of Impactor crosslink data, about 80 kbps of the available 200 kbps downlink rate must go to the Impactor up until the Impact event terminates the crosslink (this 80 kbps returns only 50 kbps of real Impactor science data).

The DSN tracking schedule in the current mission plan provides the coverage and data rates shown in Table II.

Spacecraft thermal constraints limit the allowed attitude of the vehicle with respect to the Sun direction. Normally, the spacecraft is oriented with its *Y*-axis pointed within 30° of the Sun. When the desired science targets require spacecraft

TABLE II

DI DSN tracking coverage plan.

Mission period	Allocated DSN (m)	Passes/day	S/C antenna	Data rate (kbps)
L to L + 7 d	34	3	Low gain	20
L+7 d to L+20 d	34	3	High gain	200
L+20 d to L+30 d	34	1	High gain	200
February 25	34	1	High gain	200
March 23	34	1	High gain	200
April 21	34	1	High gain	40
I-60 d to I-3 d	34	1	High gain	40
I-3 d to I-2 d	34	3	High gain	40
I-2 d to I+1 d	70	3	High gain	200
I+1 d to I+2 d	34	1	High gain	32
I+2 d to I+30 d	34	1/7 d	High gain	20

attitudes outside this range, the time permitted in those orientations is limited to 15 min out of any 4-h period to keep all subsystems within their allowable temperature range. This constraint comes into play during the early comet approach phase (prior to I-10 d) and for certain desirable calibration targets during cruise. The most significant impact of this constraint is that it imposes 4-h gaps in the rotation phase sampling of the nucleus during its early approach.

Finally, the pointing range of the high-gain antenna (HGA) is limited to the +X hemisphere. Therefore, real-time communication at high data rate is not possible for spacecraft orientations that place the Earth outside this hemisphere. This is the case during the post-flyby lookback phase. As a result, all lookback data must be stored in a buffer memory for later playback. This means that enough buffer memory must be either held open for lookback data (at the expense of impact crater data) or that some data stored in memory earlier must be played back and then written over by subsequent lookback data.

3. Data Return Strategy

The constraints on the DI data return strategy imposed by the available downlink data rates were discussed above. Our inability to return data as fast as we acquire it forces us to buffer most of the high-priority data associated with the impact event and its aftermath. The subset of data that we can return in near real time has been selected with care so that if the Flyby spacecraft should suffer damage due to a high-velocity dust impact near closest approach, we would have returned the data necessary to meet our mission success criteria. We call this our "live-for-the-moment" data return strategy. The data selected for immediate real-time playback include (a) the best-resolution color images and IR long-slit spectra of the entire nucleus pre-impact, (b) the best-resolution color images and IR long-slit spectra of the impact site pre-impact, (c) visible images and IR long-slit spectra of the impact site and the ejecta cone within $\leq$0.7 s of impact and at sampling intervals from 0.06 s to 30 s for the first 60 s thereafter plus two additional samples before I+660 s, (d) long-slit IR spectra of the coma before impact and after I+660 s, and (e) final highest-resolution images of the crater at resolutions of 2.1 and 1.4 m/pixel (HRI) and 10.3 and 7.2 m/pixel (MRI). All ITS data during the last hour prior to impact are also returned in real time.

The data selected for immediate real-time playback remain stored in buffer memory for a second playback after closest approach. The rest of the prime DI data that are not selected for real-time return are also stored in memory for later playback. The most critical data, including those right at impact, are stored redundantly on both computer strings. Some of the other data are stored on only a single string so as to increase the total amount of unique data returned in the most likely case that both computer strings remain alive and well. The data selected for non-redundant storage are all data that are functionally redundant. For example, we will chose to store every other sample of a time sampled series in alternate strings so that if one computer is lost, we still get reasonable time sampling, but if both computers survive, we get double the sampling frequency. Between I-1 h and closest approach, all the IR spectrometer data are stored redundantly, because a hardware feature disables the spectrometer data channel to the opposite computer string when data are stored only to one string. Resetting the data channel frequently was deemed too operationally complex to do during the critical encounter period.

Playback of the prime stored data (2×309 MB $= 618$ MB total) will only require about 9 h of downlink time to the scheduled 70-m DSN stations. The data should be successfully returned within about one day after closest approach interleaved between lookback imaging sessions.

4. Planned Data Set

The DI science data set that is planned is consistent with the mission and spacecraft capabilities and constraints and will, if successfully obtained, meet all of the science requirements of the mission. The data planned are summarized here by purpose and mission phase.

4.1. Instrument Calibration

Instrument calibration data are planned to be obtained starting within a few days after launch, approximately monthly during the cruise to Tempel 1, and on either side of the impact event. The initial post-launch calibrations will take advantage of the only opportunity to observe targets that fill all, or a large fraction, of the instruments' fields of view (FOV), i.e., the Moon and the Earth. Radiometric, point-spread, modulation-transfer function, and in-field scattered light response calibrations will be performed with each instrument. Images of the Moon, the Earth, and at least one star will be acquired with the HRI and MRI cameras and the IR spectrometer nominally at L+3d (L = launch). The Moon and the Earth will overfill the HRI FOV, but will only partly fill the MRI and IR FOVs. These targets will be illuminated at about 90° solar phase angle. Small scans of the IR slit across portions of the targets are planned. A set of dark frames will be acquired with each instrument, and internal stimulus flat field images will also be acquired in each visible camera.

Scattered light tests involving long-exposure imaging with the Moon positioned at various angles close to, but outside, the instruments' FOVs are planned. This out-of-field scattered light calibration will be done with the MRI at L+9 d and by the HRI (both visible and IR) at L+30 d.

The Impactor spacecraft is not scheduled to be powered on until L+10 d, and the first ITS calibration occurs nominally on L+13 d. The ITS will also view the

Moon, the Earth, and a star; however, its FOV will be even less covered by the extended targets. Dark frames and internal stimulus images will be acquired by the ITS as well.

The focus of the HRI camera will be monitored using star images as the planned post-launch bakeout of moisture absorbed by its telescope composite structure progresses. Current plans include such images at L+14 d. In addition, calibrations using celestial bodies are planned by the optical navigation team at various times during the post-launch and cruise phases.

The cruise science calibrations will include dark frame sets, internal visible stimulus images, and imaging of various celestial sources. Star clusters will be included for calibrating any geometric distortion in the images. Radiometric standard sources will permit absolute radiometric response and linearity calibrations through each spectral filter as well as point-spread determinations of spatial resolution. A number of different standard sources of various spectral classes and brightnesses are used for cross correlation and to improve spectral response modeling across filters with widely varying response rates. Stars, nebulae, and galactic clusters with known spectral emission lines will be used for IR spectral calibration. The planned set of calibration sources is summarized in Table III.

TABLE III

Celestial sources planned for use in DI inflight instrument calibrations.

Target	Spectral class	V_{mag}	RA	Dec	Viewability	Notes
HD60753	B2	6.7	113.36	−50.58	Continuous	Hot standard, few absorption lines, VIS
i Car	B3	3.9	137.82	−62.32	Continuous	Hot standard, few absorption lines, VIS
bet Hyi	G2	2.8	6.44	−77.25	Continuous	Solar analog, VIS and IR
16 CygA	G1.5	5.96	295.45	50.53	Continuous	Solar analog, VIS
Vega	A0	0.03	279.23	38.78	Continuous	Bright standard, VIS and IR
Achernar	B3	0.5	24.43	−57.24	Continuous	Bright standard, VIS
Canopus	F0	−0.72	95.99	−52.70	Continuous	Bright standard, VIS
M11			282.77	−6.27	Feb–April 2005	Cluster for geometric calibration, VIS
Pleiades			56.5	24.2	Feb/Mar 2005	Bright cluster for geometric calibration, VIS and IR
NGC3114			150.68	−60.12	Continuous	Cluster for geometric calibration, VIS and IR
NGC7027			316.76	42.23	Apr 2005 and later	Best IR spectral calibrator
NGC6543			269.64	66.63	Continuous	IR spectral calibrator
Sirius	A1	−1.45	101.28	−16.72	Feb–May 2005	IR radiometric standard

The final pre-impact calibrations using celestial sources are planned for I-40 d and I-5 d. A final set of dark frames and internal visible stimulus flat fields is planned for each instrument at I-10 h. The final post-impact calibration will occur at about I+3 d and will again use celestial sources.

4.2. Approach Data

Approach science data acquisition will begin at I-60 d. The scientific objectives of the approach phase are:

- Determine the shape of the nucleus
- Map albedo, color, and spectral variations over the entire surface for indications of heterogeneity
- Determine the rotational state of the nucleus
- Identify large-scale structures in the coma and trace them to their origin on the surface
- Monitor the nucleus to properly characterize its state of activity at the time of impact
- Search for satellites or escaping objects for a possible nucleus mass constraint
- Map the evolution of inner coma structure over a full rotation period.

Regular comet sampling with the Flyby instruments is planned covering the coma and the nucleus as it rotates. The solar phase angle of the nucleus increases by about 0.5°/day, from 28° at the start of the approach phase to 60° at I-7 d. The nominal 6-km diameter nucleus will first be spatially resolved (diameter equal to one pixel) by the HRI camera about 3 d before encounter. The nucleus is expected to remain unresolved by the MRI and IR spectrometer throughout this period. Table IV summarizes the data collection plan. All data are returned uncompressed within 24 h of acquisition.

TABLE IV

DI approach data collection plan.

Time period	Sampling frequency	HRIVIS	MRIVIS	IR	Data volume per sample (Mb)
I-60 d to I-3 d	1 every 4 h	256^2, 8-color	256^2, 8-color	64^2, 512 wavelengths	50
I-3 d to I-2 d	1 every 2 h	256^2, 8-color	256^2, 8-color	64^2, 512 wavelengths	50
I-2 d to I-1 d	1 every hour	512^2, 8-color	512^2, 8-color	512×50, 1024 wavelengths	487

4.3. IMPACTOR DATA

Shortly after its release from the Flyby at I-1 d, the Impactor ITS begins acquiring data and telemetering it over the S-band crosslink back to the Flyby. The initial data are for engineering and navigation purposes. Science imaging begins at I-22 h with a pair of full-frame images – one exposed for the nucleus and one exposed for the dimmer coma. Similar image pairs are obtained every 2 h up to I-12 h. Navigation imaging is obtained during the intervals between the science image pairs. The nucleus should equal one pixel in diameter at about I-16 h. At I-12 h, a demonstration of the final 2 min of science data acquisition before impact is conducted to verify that the Impactor will execute this critical portion of its observing sequence correctly and to allow for a fix attempt if for some unexpected reason it does not. At I-10 h, just prior to acquiring the standard image pair, an ITS dark-frame and internal stimulus calibration sequence is scheduled.

Table V summarizes the ITS observing sequence after I-20 h. Note that the ITS images serve to some extent as a backup to the MRI images from the Flyby except that the ITS has only a clear filter. The nucleus will fill the selected ITS FOV starting at about I-4 min. The ITS boresight is pointed at the expected impact

TABLE V
ITS data collection plan.

Time	Pixel scale (m)	Prime
I-20 h to I-12 h	7200–4320	1024^2 normal & long exp pair every 2 h
I-12 h	4320	Pre-impact demo; I-2 min to Impact
I-10 h		Calibration
I-10 h to I-8 h	3600–2880	1024^2 normal & long exp pair every 2 h
I-7 h to I-4 h	2520–1440	1024^2 normal & long exp pair every 1 h
I-3 h to I-1 h	1080–363	1024^2 normal & long exp pair every 0.5 h
I-1 h to I-34 m	363–210	1024^2 every 10% of time to impact (6 frames)
I-30 m	181	256^2 long exp
I-30 m to I-19 m	181–116	1024^2 every 10% of time to impact (6 frames)
I-17 m	105	512^2
I-16 m	95	512^2 normal and 256^2 long exp
I-14 m to I-9 m	87–54	512^2 every 10% of time to impact (6 frames)
I-8 m	49	512^2 normal and 256^2 long exp
I-7 m to I-5 m	45–30	512^2 every 10% of time to impact (5 frames)
I-278 s	28	512^2 normal and 256^2 long exp
I-250 s to I-70 s	25–7	256^2 every 10% of time to impact (17 frames)
I-70 s to I-17 s	7–1.8	128^2 every 10% of time to impact (16 frames)
I-16 s to I-13 s	1.6–1.3	64^2 about every 1 s (4 frames)
I-12 s to I + 2 s	1.2–0.1	64^2 every 0.7 s (20 frames)

site until I-4 min, at which time it is repointed to align with the relative velocity vector. During the last 30 s before impact, the ITS imaging rate is the maximum that can be transmitted across the crosslink. The last image expected to be transmitted in its entirety before impact is taken at about I-2 s and will have a scale of about 20 cm/pixel. Chances are larger than 50:50 that images taken after I-10 s could be lost due to dust impacts causing pointing errors. All ITS data are returned compressed from 14 to 8 bits using one of the selectable lookup table conversions.

4.4. Pre-Impact Flyby Data

Flyby science data acquired during the last day before impact comprises sets of color images and IR spectrometer scans taken at regular intervals as spatial resolution increases. The nucleus will be one pixel in diameter for the MRI and IR spectrometer at about I-16 h. Data are returned immediately after acquisition up until I-5 h. VIS data up to that time are all returned uncompressed. IR data prior to I-5 h are a mixture of compressed and uncompressed data, some binned 2×2 and some unbinned.

At I-5 h, the science storage memory is erased completely in preparation for storing the highest resolution, critical data bracketing the impact event. This erasure is done under sequence control to ensure it happens on time; data played back in the last couple of hours prior to this erasure will be at some risk since there will be no time to request a replay if they are not successfully downlinked on the first try. Almost all data between I-5 h and closest approach are stored for post-flyby playback, some redundantly and some not. A few selected data sets taken prior to I-1 h are designated for real-time playback with immediate erasure from memory after they are played back. Hourly clear-filter long-exposure frames are planned in an attempt to detect the dark limb of the nucleus for improved shape modeling.

The frequency of data sampling accelerates as resolution improves and impact approaches. Scans of the IR slit across the nucleus are performed to generate spectral maps. The ends of the IR slit typically extend well beyond the nucleus to give spectral measurements of the coma (albeit likely to be at reduced signal-to-noise ratio due to short exposures). Tables VI–VIII summarize the Flyby science data taking scenarios for each instrument during the last day prior to impact. The column labeled "Prime" indicates data stored for post-flyby playback. The column labeled "R/T" indicates the data that are scheduled for immediate playback. From about I-13 min through closest approach, the queue of data for immediate playback contains a backlog. The table entries are color coded to indicate color sets, uncompressed data, and data stored on only a single computer string. Just prior to impact, the nucleus will fill about 1/3 of the HRI FOV and about 70 MRI and IR spectrometer pixels. Except during IR scans, the instrument boresights are targeted to the predicted impact point; no mosaicking is planned. Expected mean signal-to-noise ratios (SNRs) and 3σ smear levels for the selected exposure times are given

TABLE VI

HRIVIS pre-impact data collection plan.

Time	Pixel scale (m)	Prime	R/T
I-25 hr	1830		3-clear + 7 color 512^2 set
I-23 hr	1697		3-clear + 7 color 512^2 set
I-21 hr	1540		3-clear + 7 color 512^2 set
I-19 hr	1400		3-clear + 7 color 512^2 set
I-17 hr	1250		3-clear + 7 color 512^2 set
I-15 hr	1100		3-clear + 7 color 512^2 set
I-13 hr	960		3-clear + 7 color 512^2 set
I-12 hr	890		3-clear 512^2
I-11 hr	815		3-clear + 7 color 512^2 set
I-10 hr			Calibration
I-10 hr	740		3-clear 512^2
I-9 hr	670		3-clear + 7 color 512^2 set
I-8 hr	600		3-clear 512^2
I-7.5 hr	560		3-clear 512^2
I-7 hr	525		3-clear + 7 color 512^2 set
I-6.5 hr	490		3-clear 512^2
I-6 hr	450		3-clear + 7 color 512^2 set
I-5 hr	380		3-clear + 7 color 512^2 set
I-4.5 hr	345	3-clear 512^2 + 256^2 long exp	3-clear 512^2 + 256^2 long exp
I-4 hr	310	3-clear + 7 color 512^2 set	3-clear + 7 color 512^2 set
I-3.5 hr	270	256^2 long exp	3-clear 512^2 + 256^2 long exp compr
I-3 hr	235	3-clear + 7 color 512^2 set	3-clear + 7 color 512^2 set
I-2.5 hr	200	256^2 long exp	3-clear + 7 color 512^2 set + 256^2 long exp compr
I-2 hr	163	3-clear + 7 color 512^2 set	3-clear + 7 color 512^2 set
I-1.5 hr	127	256^2 long exp	3-clear + 7 color 512^2 set + 256^2 long exp compr
I-1 hr	90	3-clear + 7 color 512^2 set	3-clear + 7 color 512^2 set
I-40m	66	128^2 8-color	128^2 8-color
I-27m	50	256^2 8-color +256^2 long exp compr	256^2 8-color + 256^2 long exp compr
I-18m	39	256^2 8-color	256^2 8-color
I-10m	29	8-color set; 7 @ 512^2, 1 @ 1024^2	
I-3.5m	21	8-color set; 7 @ 512^2, 1 @ 1024^2	
I-32s to I-7s	18	5-color set; 4 @ 512^2, 1 @ 1024^2	4-color set @ 512^2, 1 @ 1024^2
I-7s to I-3s	17	1024^2	

=>color set

=>one-string storage

=>uncompressed data

=>uncompressed and one-string storage

TABLE VII
MRIVIS pre-impact data collection plan (see Table VI for key to color coding).

Time	Pixel scale (m)	Prime	R/T
I-26 hr	9520		8 color 512^2 set
I-22 hr	8070		8 color 512^2 set
I-20 hr	7350		8 color 512^2 set
I-18 hr	6620		8 color 512^2 set
I-16 hr	5900		8 color 512^2 set
I-14 hr	5170		8 color 512^2 set
I-12 hr	4440		8 color 512^2 set
I-12 hr	4300		5 512^2 long-exposure gas filters
I-10 hr	3720		8 color 512^2 set
I-10 hr			Calibration
I-8 hr	2990		8 color 512^2 set
I-7 hr	2630		8 color 512^2 set
I-6 hr	2270		8 color 512^2 set
I-6 hr	2150		5 512^2 long-exposure gas filters
I-5 hr	1900	8 color 512^2 set	8 color 512^2 set
I-4 hr	1540		8 color 512^2 set
I-3 hr	1180	8 color 512^2 set	8 color 512^2 set
I-2.5 hr	1000		8 color 512^2 set
I-2 hr	815	8 color 512^2 set	8 color 512^2 set
I-1.5 hr	635		8 color 512^2 set
I-1 hr	453	8 color 512^2 set	8 color 512^2 set
I-40m	330	128^2 8-color	128^2 8-color
I-27m	250	256^2 8-color	256^2 8-color
I-18m	194	256^2 long exp	256^2 long exp
I-18m	194	256^2 8-color	256^2 8-color
I-10m	144	8-color set; 1024^2	3-color set; 1024^2
I-3.5m	105	8-color set; 7 @ 512^2, 1 @ 1024^3	
I-32s to I-7s	88	7-color set; 1024^2	4-color set @ 1024^2
I-7s to I-3s	87	1024^2	1024^2

in Table IX. For the IR spectrometer, the table lists several selected wavelengths and predictions at the longer wavelengths for scenes with surface temperatures of 200 K outside the anti-saturation filter that covers the central one-third of the slit and for surface temperatures of 300 K behind the anti-saturation filter (300 K surfaces outside the filter will saturate at these wavelengths). Note that when using the minimum exposure times for IR subframe modes, the smear and SNR will be somewhat lower (by roughly the square-root of the exposure time ratio).

4.5. Flyby Data at Impact

The primary science objective during the impact event is to observe at high time resolution the physics of the event and the nature and geometry of the material

TABLE VIII

IR spectrometer pre-impact data collection plan.

Time	Binned pixel scale (m)	Prime	R/T
I-25 to I-11 hr	9160 - 4077		512-hi column x 50-wide scan every 2 hr; uncompressed
I-10 hr			Calibration
I-9 hr	3352		512-hi column x 50-wide scan
I-7 hr	2626		256-hi column x 50-wide scan; uncompressed
I-6 hr	2263		512-hi column x 50-wide scan
I-5 hr	1900	Clear NVM after last sample	256-hi column x 50-wide scan
I-4 hr	1440	128-hi column x 50-wide scan	256-hi column x 50-wide scan; uncompressed
I-3 hr	1080	128-hi column x 50-wide scan	512-hi column x 50-wide scan
I-2.5 hr	980		256-hi column x 50-wide scan; uncompressed
I-2 hr	810	128-hi column x 50-wide scan	256-hi column x 50-wide scan
I-1.5 hr	615		512-hi column x 50-wide scan
I-1 hr	440	128-hi column x 50-wide scan	256-hi column x 50-wide scan
I-36m	300	64-hi column x 40-wide scan over full nucleus	
I-19m	200	64-hi column x 64-wide scan over full nucleus; central 32 slits stored uncompressed	64-hi column x central 32-wide scan over full nucleus
I-14m	167	512-hi column unbinned on nucleus	
I-13m	166	512-hi column unbinned off edge of nucleus	
I-13m	160	256-hi column x 64-wide partial scan of coma	256-hi column x central 48-wide partial scan of coma
I-10m	146	512-hi column unbinned off edge of nucleus	
I-6m	125	64-hi column x 64-wide scan over full nucleus	
I-190s to I-66 s	95	128-hi column x 84-wide scan over full nucleus	One 128-hi column centered on impact site
I-35s to I-9 s	87	256-hi columns every 2.88 s	256-hi columns every 2.88 s

=>uncompressed, unbinned data

=>unbinned, compressed

initially ejected from the crater. Flyby instruments are trained on the predicted impact point and commanded to acquire data at high rate starting a few seconds before the expected time of impact and for some time thereafter. The predicted uncertainty in the actual time of impact calculated onboard by the autonav algorithms is about 3 s. MRIVIS images are taken at the maximum possible rate of 0.06 s by restricting its format to 64^2 in order to obtain the highest possible time resolution of the

TABLE IX
Predicted smear and nucleus signal-to-noise ratios for nominal exposures.

HRIVIS	Nominal exposure time (ms)	3σ smear (pixel)	Mean SNR
1-Clear	100	1.5	89
2-450 nm	500	2.75	69
3-550 nm	400	2.65	87
4-350 nm	700	3	48
5-950 nm	700	3	52
7-750 nm	400	2.65	74
8-850 nm	500	2.75	64
9-650 nm	400	2.65	85
MRIVIS			
1-Clear	100	0.4	174
2-514 nm	3000	0.8	144
3-526 nm	2500	0.75	89
4-750 nm	500	0.55	163
5-950 nm	2000	0.7	166
7-387 nm	3000	0.8	61
8-345 nm	3000	0.8	29
9-309 nm	7000	0.9	23
IR Spectrometer			
1.2 μm	2880	1.56	27
2 μm	2880	1.56	55
2.8 μm (300 K, filt)	2880	1.56	102
3.6 μm (300 K, filt)	2880	1.56	287
4.6 μm (300 K, filt)	2880	1.56	17
2.8 μm (200 K, no filt)	2880	1.56	42
3.6 μm (200 K, no filt)	2880	1.56	37
4.6 μm (200 K, no filt)	2880	1.56	55

impact event and its photometric light curve. The FOV should still be large enough to ensure capturing the impact site given the expected level of pointing errors and uncertainty in the impact site location (in fact, the selected FOV covers nearly the entire nucleus). This imaging rate is maintained up to 6 s after the nominal impact time. During this period, the HRI images are taken one-fourth as often but with a 256^2 image format. This approach yields comparable areal coverage as the MRI but with five times the spatial resolution. The IR spectrometer meanwhile is obtaining fixed-slit spectra centered on the predicted impact site every 0.72 s, its fastest frame rate, using a 64-pixel slit length.

The onboard data storage limitations prohibit continuing sampling at these high rates indefinitely, and we also wish to expand the instrument FOVs to capture more of the outflowing ejecta cone as time progresses. Therefore, we begin to step up the frame formats and decrease the sampling rate as time from impact increases. Tables X–XII list the data acquisition plan from impact until I+24 s for each instrument.

TABLE X
HRIVIS impact data (see Table VI for key to color coding).

Time	Pixel scale (m)	Prime	R/T
I-3s to I-0.5s	17	256^2 every 0.24 s	256^2 every 0.72 s
I-0.5s to I+1s	17	256^2 every 0.24 s	256^2 every 0.24 s
I+1s to I+7s	17	256^2 every 0.24 s	256^2 every 0.72 s
I+8s to I+9s	17	256^2 every 0.72 s	256^2 @ I+8s
I+9.5s	17	256^2	
I+10s	17	256^2	256^2
I+11s to I+15s	17	512^2 every 1.02s	512^2 @ I+13s
I+15s to I+20s	17	512^2 every 1.1s	512^2 @ I+16s
I+21s	17	512^2	
I+22s to I+24s	17	512^2 every 1.1s	512^2 @ I+22s

TABLE XI
MRIVIS impact data (see Table VI for key to color coding).

Time	Pixel scale (m)	Prime	R/T
I-3s to I-0.5s	86	64^2 every 0.06 s	64^2 every 0.24 s
I-0.5s to I+1s	86	64^2 every 0.06 s	64^2 every 0.06 s
I+1s to I+6s	85	64^2 every 0.06 s	64^2 every 0.24 s
I+7s to I+9s	85	128^2 every 0.12 s	128^2 every 1 s
I+10s	85	256^2	
I+11s to I+17s	84	256^2 every 0.72s	256^2 every 4 s
I+17s to I+20s	84	512^2 every 1.1s	
I+21s	84	512^2	
I+22s to I+24s	84	512^2 every 1.1s	512^2 @ I+22s

TABLE XII
IR spectrometer impact data (see Table VIII for key to color coding).

Time	Pixel scale (m)	Prime	R/T
I-6 s to I+4 s	86	64-hi column every 0.72 s	64-hi column every 0.72 s
I+4 s to I+15 s	85	64-hi column every 0.72 s	64-hi column every 1.44 s
I+15 s to I+24 s	83	128-hi column every 1.44 s	128-hi column every 2.88 s

A subset of the impact data is selected for real-time downlink by not selecting every time sample. All the data are compressed to 8 bits except for HRI and MRI images at I+10 s and I+21 s.

4.6. Post-Impact Data

As the crater develops and ejecta continues to flow outward, we intend to monitor this continuing process (crater formation is nominally expected to be complete within about 4 min). Sampling with all the Flyby instruments continues; however, the sampling rate gradually decreases and the FOVs are progressively enlarged so that they extend off the edges of the nucleus to capture the near-nucleus coma. The first full-format images are taken at I+24 s. The instruments remain pointed at the nominal impact site until I+50 s when a small 11-slit-wide scan across the impact site is done to obtain two-dimensional IR spectrometer coverage. This scan is repeated again at I+87 s. Color imaging resumes with both the HRI and MRI at I+67 s, and periodic color sets are obtained thereafter interspersed with 1-color images all centered on the nominal impact site (no mosaicking). Most of the 1-color images are stored in only one computer string with alternate images going to string A and string B. A few selected images are saved uncompressed.

Starting at I+125 s until I+177 s, the IR slit is again nominally pointed and held at the predicted impact point. At the end of this period, a full nucleus scan of the IR slit is performed that lasts about 5 min. The first post-impact unbinned spectra are obtained at each end and once in the middle of this scan. HRI and MRI color sets centered on the impact site are obtained and returned in real time at the end of this scan. The nucleus fills the full HRI FOV at about I+550 s.

When these color sets are completed, the instrument boresights are pointed off the nucleus to obtain coma data. Three IR spectra with a 256-pixel slit are obtained with long exposures at different locations in the coma out to about 3 km from the center of the nucleus. Following this, the last highest-resolution HRI and MRI color sets are obtained pointed at the nominal impact site. Color imaging is avoided during the last 50 s to keep filter wheel vibration from degrading the highest resolution images. After completing the last color imaging, the last IR scan of the 300-m-wide region centered on the crater is performed. This scan is completed about 25 s before the spacecraft must go into its shield mode (SM) orientation to protect itself from dust impact during the closest approach period. During the course of this scan, one 512^2 image each from the HRI and MRI is selected for real-time return; these images are the last ones whose playback will be completed prior to closest approach. From SM-25 s until SM, the instruments are again pointed directly at the nominal impact site (no mosaicking). Regularly spaced images and IR spectra are taken until entering shield mode with the second-last images being stored uncompressed and the last, highest-resolution images being selected for real-time return as well as being stored for later playback. Their playback will not be completed until about

TABLE XIII

HRIVIS post-impact data (see Table VI for key to color coding).

Time	Pixel scale (m)	Prime	R/T
I+24s to I+36s	17	1024^2 @ I+24s, 512^2 every ~2.4s	512^2 @ I+33s
I+36s	16	1024^2	
I+39s to I+67s	16	512^2 every 10% of time since Impact; 1024^2 every 40% time since Impact	512^2 @ I+58s
I+67s to I+84s	16	4-color 512^2 + 1024^2	
I+84s to I+108s	15	512^2 every 10% of time since Impact	
I+108s to I+133s	15	4-color 512^2 + 1024^2	512^2 @ I+123 s
I+141s	14	1024^2	
I+155s to I+175s	14	4-color 1024^2 set	
I+185s to I+225s	13	1024^2 every 21s	
I+248s to I+273s	12	5-color 1024^2 set	
I+295s to I+329s	11	1024^2 every 29s	
I+356s to I+372s	10	4-color 512^2 set	512^2 @ I+364s
I+404s to I+449s	9 - 8	1024^2 every 40s	
I+465s to I+479s	7	4-color 1024^2 set	
I+508s	7	1024^2	
I+558s to I+578s	6	4-color 1024^2 set	
I+623s to I+637s	4.5	4-color 512^2 set	4-color 512^2 set
I+660s to SM-100s	4 - 3	1024^2 every 4s	
SM-100s to SM-68s	3	8-color 1024^2 set	
SM-68s to SM-40s	2.8	1024^2 every 2 s	
SM-40s	2	512^2	512^2
SM-40s to SM-28s	2	1024^2 every 2 s	
SM-28s to SM-4s	1.9 - 1.5	1024^2 every 2 s	
SM-2s	1.5	1024^2	
SM	1.4	1024^2	1024^2

158 s later (108 s after closest approach, about the time of crossing the orbit of Tempel 1). The nucleus will approximately equal the MRI FOV at the time of shield-mode entry.

Tables XIII–XV present the planned science data sets for each instrument during the post-impact period.

4.7. Shield-Mode and Lookback Data

After entering shield mode, the spacecraft remains in this attitude until about 22 min after closest approach (CA) when the dust-impact hazard zone has been safely passed. While in this attitude, five long-slit IR spectra are obtained during the first

TABLE XIV

MRIVIS post-impact data (see Table VI for key to color coding).

Time	Pixel scale (m)	Prime	R/T
I+24s to I+36s	83	1024^2 @ I+24s, 512^2 every ~2.4s	512^2 @ I+33s
I+36s	82	1024^2	
I+39s to I+67s	81	512^2 every 10% of time since Impact; 1024^2 every 40% time since Impact	512^2 @ I+61s
I+67s to I+84s	79	4-color 512^2 + 1024^2	
I+84s to I+108s	76	512^2 every 10% of time since Impact	
I+108s to I+133s	74	4-color 512^2 + 1024^2	512^2 @ I+123 s
I+141s	70	1024^2	
I+155s to I+175s	68	4-color 1024^2 set	
I+185s to I+225s	63	1024^2 every 21s	
I+248s to I+273s	60	5-color 1024^2 set	
I+295s to I+329s	53	1024^2 every 29s	
I+356s to I+372s	49	4-color 512^2 set	512^2 @ I+364s
I+380s to I+449s	41	1024^2 every 40s	
I+465s to I+485s	38	4-color 1024^2 set	
I+508s	35	1024^2	
I+558s to I+578s	29	4-color 1024^2 set	
I+623s to I+637s	23	4-color 256^2 set	4-color 256^2 set
I+660s to SM-100s	18	1024^2 every 4s	
SM-100s to SM-52s	14	8-color 1024^2 set	
SM-52s to SM-40s	12	1024^2 every 2 s	
SM-40s	10	512^2	512^2
SM-40s to SM-28s	10	1024^2 every 2 s	
SM-28s to SM-4s	9 - 8	1024^2 every 2 s	
SM-2s	7	1024^2	
SM	7	1024^2	1024^2

minute after entering shield mode using long integration times to sample the near nucleus coma emissions. Since the spacecraft is traveling at 10 km/s relative to the comet and the pointing attitude is fixed, even with the minimum available integration time of 2.88 s, the IR spectra would be smeared over nearly 30 km of the coma in the along-track direction. Since good spatial resolution is not possible anyway, longer integration times of 7 and 14 s are planned to allow lower detection limits for any faint coma emissions that persist over many kilometers of the coma. The last such spectrum will be obtained when the spacecraft is near closest approach and the IR spectrometer FOV is looking at a point about 500 km behind the nucleus on a line parallel to the spacecraft flight direction and passing through the nucleus.

TABLE XV

IR spectrometer post-impact data (see Table VIII for key to color coding).

Time	Binned pixel scale (m)	Prime	R/T
I+24 s to I+32 s	83	128-hi column every 1.44 s	128-hi column every 2.88 s
I+32s to I+50s	81	256-hi column every 2.88 s	256-hi column at I+35s
I+50s to I+67s	80	128-hi column x 11-wide crater scan	One 128-hi column
I+70s	79	256-hi column	
I+77s	78	256-hi column	
I+84s	77	256-hi column	
I+87s to I+107s	76	128-hi column x 11-wide crater scan	One 128-hi column
I+110s to I+154s	71	256-hi column every 10% time from impact	
I+167s	69	256-hi column	
I+180s	68	512-hi column unbinned at edge of nucleus	
I+188s to I+246s	65	128-hi column x 40 wide scan of first part of nucleus	
I+250s	61	512-hi column unbinned at middle of nucleus	
I+255s to I+484s	60 - 38	256-hi column x 80 wide continuation scan of remainder of nucleus	
I+490s	37	512-hi column unbinned at edge of nucleus	
I+497s to SM-142s	37 - 21	256-hi column x 60 wide scan of central 1/4 nucleus	
SM-130s to SM-110s	18	Three 256-hi columns in coma; middle one uncompressed	One 256-hi column in coma
SM-98 s to SM-26 s	16 - 9	256-hi column every 2.88 s; 25-wide scan of 3x crater diameter	64-hi column every 2.88 s; 25-wide scan of 3x crater diameter
SM-23 s to SM-3 s	8	256-hi column every 2.88 s	
SM-3s to SM	7	256-hi column	256-hi column

At CA+22 min, the spacecraft begins an attitude maneuver to point the instruments back toward the nucleus. This maneuver takes about 9 min to complete. At that time, the first lookback science data of the nucleus and its surroundings are acquired. Eight-color sets are taken with both the HRI and MRI along with multi-frame sets (for co-adding) in the clear-filter using both normal and extended exposure times to image well both the nucleus and the coma as it evolves and to potentially locate and track any large debris from the impact that might be in orbit about the nucleus. The nucleus easily fits within the HRI FOV at this time and subtends only about 30 MRI pixels. These images should also map new areas of the nucleus surface at better resolution than on approach and

TABLE XVI
HRIVIS shield-mode and lookback data (see Table VI for key to color coding).

Time	Pixel scale (m)	Prime	R/T
SM+31m	36	11 1024^2 (3 long exp)	
SM+38m	44	6 1024^2 (3 long exp)	
SM+41m	48	6 1024^2 (3 long exp)	
SM+46m	56	6 1024^2 (3 long exp)	
SM+51m	60	6 1024^2 (3 long exp)	
SM+56m	66	6 1024^2 (3 long exp)	
SM+1 hr	73	6 1024^2 (3 long exp)	
SM+2 hr	145		18 1024^2 (5 long exp)
SM+3 hr	218		18 1024^2 (5 long exp)
SM+4 hr	290		18 1024^2 (5 long exp)
SM+5 hr	363		18 1024^2 (5 long exp)
SM+6 hr	435		18 1024^2 (5 long exp)
SM+12 hr	871		18 1024^2 (5 long exp)

help constrain the three-dimensional shape of the nucleus by mapping newly lit limbs as the nucleus rotates. IR long-slit spectra are taken at three coma positions, and a scan is done across the nucleus. The departure solar phase angle is about 116°.

HRI clear-filter sets of normal and extended exposures are acquired approximately every 5 min for the next 30 min (out to 1 h after CA). IR spectral sampling is repeated at about CA+40 min and CA+60 min. HRI color and multi-frame clear sets are repeated every hour out to CA+6 h and a final HRI sample is taken at CA+12 h. MRI color sets and multi-frame clear sets and IR coma samples at 3 positions (unbinned) are scheduled every 2 h out to CA+6 h and every 6 h out to CA+60 h to cover just over one full nucleus rotation.

Tables XVI–XVIII list the shield-mode and lookback data sets for each instrument. The data up to CA+1 h are stored as prime data for later playback. At this point the memory buffer is completely full of science data. Starting after the CA+1 h data collection, a spacecraft attitude maneuver is scheduled to allow playback and erasure of some of the initial lookback data from the memory buffer to free up space for the next lookback samples at CA+2 h. Attitude maneuvers are required for data return in this phase because the HGA is pointed away from the Earth in the lookback data-taking attitude. This pattern is repeated between each of the remaining lookback samples, which is why these data are listed only in the real-time column in Tables XVI–XVIII. After CA+6 h, the intervals between lookback samples increase to 6 h. The interleaved downlink sessions then become long enough to playback not only the previous lookback data set but also some of the prime data stored in memory. Playback of the prime data should be complete by CA+24 h.

TABLE XVII
MRIVIS shield-mode and lookback data (see Table VI for key to color coding).

Time	Pixel scale (m)	Prime	R/T
SM+30m	181	18 1024^2 (5 long exp)	
SM+2h	725		18 1024^2 (5 long exp)
SM+4h	1451		18 1024^2 (5 long exp)
SM+6h	2177		18 1024^2 (5 long exp)
SM+12h	4354		18 1024^2 (5 long exp)
SM+18h	6531		18 1024^2 (5 long exp)
SM+24h	8709		18 1024^2 (5 long exp)
SM+30h	10886		18 1024^2 (5 long exp)
SM+36h	13063		18 1024^2 (5 long exp)
SM+42h	15240		18 1024^2 (5 long exp)
SM+48h	17418		18 1024^2 (5 long exp)
SM+54h	19595		18 1024^2 (5 long exp)
SM+60h	21772		18 1024^2 (5 long exp)

5. Data Calibration

To be able to make full scientific use of the data gathered by the DI instruments during the mission, the raw data numbers (DNs) returned from each pixel in each image or spectrum must be converted to absolute scientific units of scene radiance or scene reflectance. The effective wavelength of the photons that generated the signal in each pixel must be known. In addition, it must be possible to determine from where in the scene or its surroundings the photons originated that produced the signal in each pixel. Accomplishing these functions is the goal of data calibration.

Figures 1 and 2 illustrate the planned DI radiometric calibration data processing pipeline. No correction for any instrument coherent noise is included in this plan since, although the final detailed analysis of the ground calibration data to search for evidence of coherent noise is not yet compete, no signs of such noise have yet been observed. While some evidence of electrical crosstalk between CCD quadrants has been observed for extremely high signal levels, this effect has not yet been fully characterized, and no noise removal algorithm has yet been derived. No correction for any spectral crosstalk in the IR spectrometer is currently included. While we found significant spectral crosstalk in the instrument during initial ground calibrations, steps were taken to eliminate its cause. Detailed analysis of any remaining crosstalk is not yet complete; however, no evidence of any obvious crosstalk was seen after the instrument corrections were implemented. The steps of the pipeline process are discussed in the following paragraphs.

To obtain the highest accuracy, calibration data are ordinarily returned uncompressed. Calibration correction files are then constructed using full 14-bit accuracy.

TABLE XVIII

IR spectrometer shield-mode and lookback data (see Table VIII for key to color coding).

Time	Binned pixel scale (m)	Prime	R/T
SM+3s to SM+21s	7	2 256-hi columns, 7-s exposure	
SM+24s to SM+1 min	5 - 30	256-hi columns every 14 sec, 14-s exposure	
SM+33m	190	256-hi columns at 3 coma positions plus 60-slit scan across nucleus	
SM+42m	250	256-hi columns at 3 coma positions plus 50-slit scan across nucleus	
SM+62m	375	256-hi columns at 3 coma positions plus 30-slit scan across nucleus	
SM+2 hr	744		512-hi columns at 3 coma positions
SM+4 hr	1470		512-hi columns at 3 coma positions
SM+6 hr	2190		512-hi columns at 3 coma positions
SM+12 hr	4370		512-hi columns at 3 coma positions
SM+18 hr	6550		512-hi columns at 3 coma positions
SM+24 hr	8725		512-hi columns at 3 coma positions
SM+30 hr	10900		512-hi columns at 3 coma positions
SM+36 hr	13080		512-hi columns at 3 coma positions
SM+42 hr	15260		512-hi columns at 3 coma positions
SM+48 hr	17435		512-hi columns at 3 coma positions
SM+54 hr	19615		512-hi columns at 3 coma positions
SM+60 hr	21790		512-hi columns at 3 coma positions

For flight data that are returned compressed to 8 bits/pixel, the first step in their calibration is to convert them back into their equivalent 14-bit values. A calibration step is also included here to correct for any possible non-uniformity in digital encoding DN intervals introduced during the initial instrument analog-to-digital data sampling (called uneven bit weighting). For the IR spectrometer, ground calibrations have shown that the output DNs do not increase linearly with integration time. Rather, the signal generation rate decreases as the total integrated signal increases.

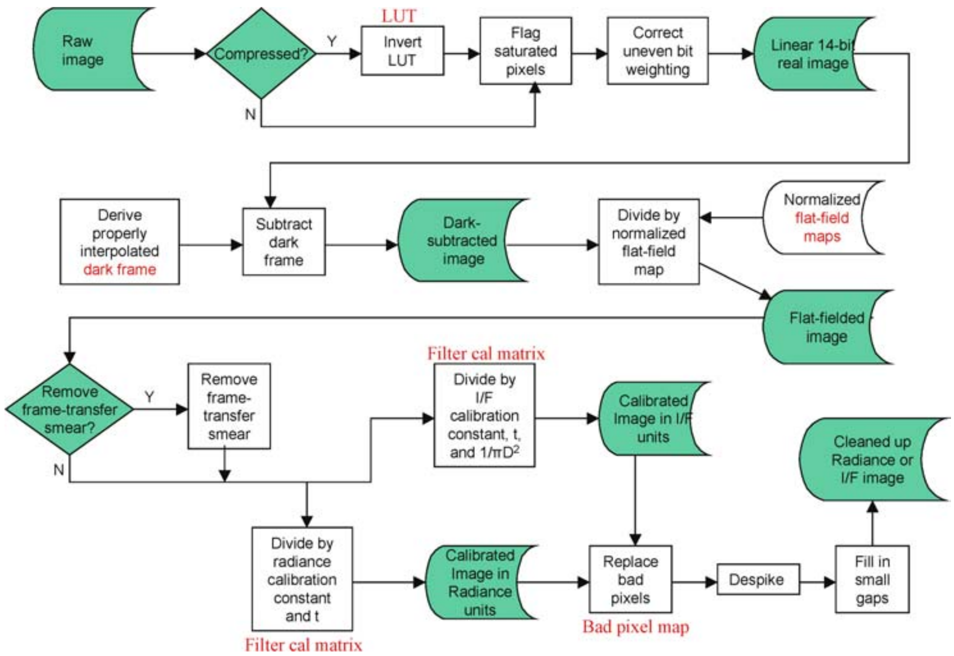

Figure 1. VIS radiometric calibration data processing pipeline.

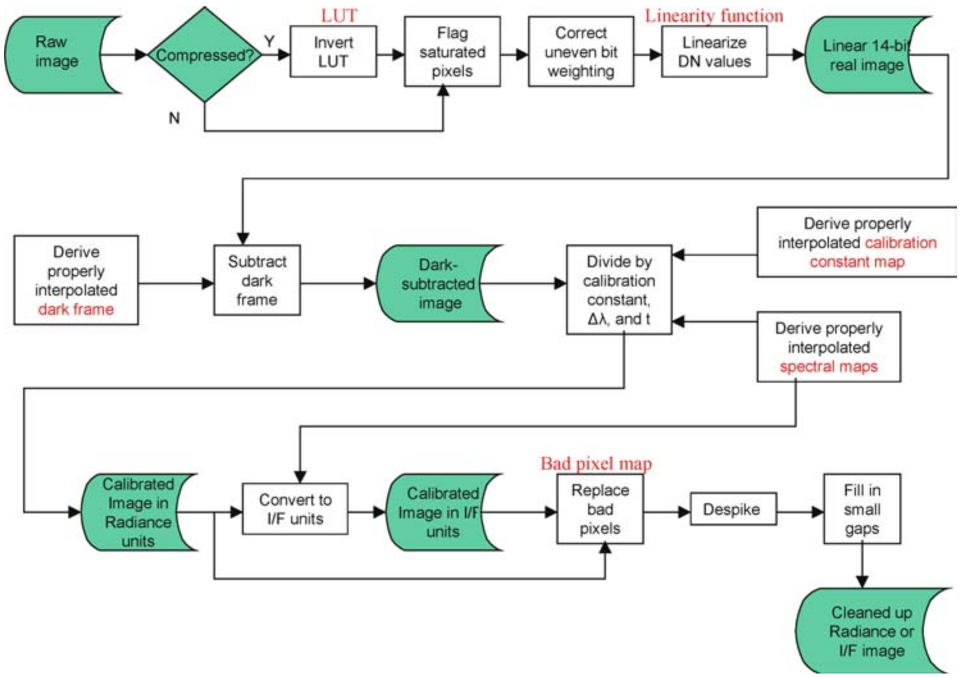

Figure 2. IR Spectrometer radiometric calibration data processing pipeline.

Therefore, a linearization step must be applied to IR data as the next step in calibration.

Radiometric calibration requires that the returned signal level in each pixel in the absence of any external scene input be determined. This offset level needs to be subtracted from the returned raw DN levels as a first step in isolating the scene-induced signal. For the IR spectrometer detector, the offset level varies with integration time, detector temperature, optical bench temperature, and to some extent the past history of detector readout. The offset level for each pixel in the CCD cameras can vary with integration time and detector temperature. For most camera operating modes, overscan pixels are returned that provide a measure of the offset for every line. However, ground calibration results analyzed to date suggest that the CCD bias level varies on time scales shorter than one line time by an amount at least comparable to the variation in the line-to-line average values. Therefore, CCD bias subtraction using averaged dark frames appears to be a better approach. "Dark" frames representing the instrument output in the absence of any scene input are acquired that span the range of independent variable values. A calibration frame properly interpolated to the parameter values that apply to a given image is subtracted as the next step in calibration.

For the VIS cameras, differences in the relative response rate of individual pixels within each detector are next removed by dividing by a normalized flat-field map. These maps will be initially derived from ground-based flat-field imagery. Updates may be performed based on the results of inflight images of the internal stimulus, the Moon, and/or the Earth; however, none of these sources will present a true flat-field to the detector, so the updates are likely to limited. The frame-transfer type of CCDs used in the VIS cameras allow some signal to be accumulated during the finite time required to shift the image from the active portion of the array to the masked storage region. This shift typically takes about 5 ms. For images that are acquired with short exposure times, this extra "smeared" signal could be detectable and a source of error in calculating scene radiance. Therefore, an optional step that removes the frame-transfer smear signal can be selected prior to converting the dark-subtracted, flat-field corrected data to radiometric units. This final radiometric conversion is done by dividing the image by a calibration constant unique for each filter position and by the commanded integration time.

For the IR Spectrometer, no single correction file can be derived to correct for pixel-to-pixel response variations because the mapping of wavelength to pixel location changes with optical bench temperature. Therefore, for the spectrometer, the flat-field and radiometric conversion steps are combined into one step. Files of wavelength, wavelength band, and calibration constant for each pixel as a function of bench temperature and instrument operating mode will be used to interpolate to the values to use for calibrating each flight image based on its bench temperature and mode.

After radiometric calibration is complete, other optional calibration steps can be applied. One possible additional correction is to clean up the image by interpolating over known bad pixel locations, removing cosmic-ray-induced noise spikes, and filling in any small gaps due to missing data. Another process that could be applied is a geometric correction for any optical distortions that might exist in the instrument. Finally, spatial resolution could potentially be improved by doing a correction for the instrument's point-spread function (or modulation transfer function) and scattered light response.

Besides the raw images, we intend to archive with NASA's Planetary Data System (PDS) the radiometrically calibrated versions of all images in both radiance and reflectance units. Any images that are selected for further calibration (cleanup, geometric correction, and/or resolution enhancement) will also be archived with PDS.

6. Data Processing Pipeline

6.1. Introduction

Each raw DI instrument frame is initially stored on the spacecraft as a single data "file." The data files are broken up into data packets, which are downlinked via the DSN to the Jet Propulsion Laboratory Advanced Multimission Operations System (JPL/AMMOS). AMMOS decommutates the packets to recreate the original raw observations. In data terms, the raw observations are simply a stream of data in a compact, mission-specific format unsuitable for scientific analysis.

6.2. Science Data Center Description – Overview

The DI Science Data Center (SDC) is located at Cornell University, and its main tasks are to

1. Receive raw observations from JPL/AMMOS
2. Convert raw observations into products suitable for analysis and archiving
3. Make the products available to the Science Team and others.

To accomplish this, the SDC comprises hardware (computers and disk storage), software, and interfaces to the various suppliers and clients of the SDC. The SDC is designed for data handling and conversion only; science team members will perform scientific analysis at their home institutions using data obtained from the SDC. The Planetary Data System-Small Bodies Node (PDS-SBN) at the University of Maryland will archive SDC products as well as Science Team products (see The Data Archive section below).

6.3. Science Data Center Description – Hardware

The hardware will be standard PC components for reasons of low cost, high reliability and simple sparing and maintenance. The SDC will be developed and built at Cornell University, but will be easily and inexpensively replicated at JPL for the encounter as well as at any other site desired.

6.4. Science Data Center Description – Software

The operating system software is Linux, chosen for its low cost, high reliability, and numerous, readily available, free, powerful development tools. The SDC-specific software will be a combination of standard Linux/Unix$^{\text{TM}}$ scripting tools and the Interactive Data Language (IDL) from Research Systems, Inc. Generally, the scripts will handle the file management tasks, and IDL software will handle the conversion of raw images into standard products. More broadly stated, the scripts will handle the data containers, and IDL will handle the data contents. The data will be organized in a database accessible to the Science Team using standard tools (PHP, a popular scripting language similar to Perl, and MySQL, a freely available database server and sequenced query language). As far as possible, the data acquisition, conversion, and delivery software will be automated.

6.5. Science Data Center Description – Interfaces

Each interface is designed around the supplier or client of the particular data or information passing through the interface.

All of the interfaces sit on top of the TCP/IP networking protocols and the Internet, which provides network access to the SDC at an arbitrary location to virtually any science team member. Interfaces transferring sensitive information will be password protected and/or encrypted via the Secure Sockets Layer (SSL) and Secure Shell (SSH) protocols.

The first interface transfers incoming data from the AMMOS to the SDC. Incoming data are pushed over the Internet by AMMOS scripts using SSH to encrypt the data. Data are run through relevant pipelines (see below), converted to standard products (see below), and made available to Science Team members and others via client interfaces in near-real time. Other data, such as commands and engineering telemetry, will be supplied by similar interfaces to this one.

The rest of the interfaces are client interfaces to post-pipeline standard products, and they all use the Hyper Text Transfer Protocol (HTTP), which makes them available to users on the Internet with a standard World Wide Web (WWW or "Web") browser.

The simplest client interface allows browsing of the directory structure of the SDC products. In this mode, the data are arranged hierarchically by mission phase (e.g. ground calibration, ground-based mission scenario tests, inflight calibrations, flyby), instrument, product type (e.g. raw, calibrated), date data were taken, and filename. The filename of each observation contains information specific to the observation in an encoded form. The main use of this interface will involve the

PDS downloading the entire dataset for archiving. It is not anticipated that this interface will get much other use unless one is trying to locate specific observations for which the filenames are already known.

The next client interface allows browsing of the data based on the synoptic environment unique to each observation. Specifically, this interface makes it possible for one to select observations using criteria from the FITS header (see Standard products below), and download one or more observations in a single step for scientific analysis. Given the large number of header keywords, this interface is very powerful but also very complex, requiring detailed knowledge of the keywords, which are restricted to sometimes cryptic mnemonics of eight characters. The interface will attempt to lessen the complexity by: (1) grouping the header keywords according to function, (2) sorting the keywords by priority assigned by the Science Team, and (3) making a description of each keyword available as part of the interface.

Another client interface is the inverse of the synoptic interface described above in that, where the synoptic interface looks backward in time at the observation environment, this interface looks at the data through the lens of the data set planning (see above). In this interface, the planned data set groupings (calibration, approach, pre-impact, impact, post-impact, etc.) will be part of the database, and the observations will be sorted as they arrive according to their original purpose or observational goal.

The details of the two previously described interfaces are described below in the section Data Library and Catalog.

Finally, Science Team products for Education and Public Outreach may be made available via a public interface to the SDC. This interface will be a typical website with the content comprising mostly images, figures and captions, generated by the Science Team and suitable for the audience.

6.6. Pipeline Processing Flow

Figure 3 summarizes the flow of data to, through, and from the SDC. The figure shows the five basic functions the SDC performs on the data: convert, validate, calibrate, store, and distribute.

The main pipeline is as follows: decommutated spacecraft files and engineering telemetry from the AMMOS and commands from the Mission Operations Center (MOC) will be converted into standard raw products. The raw products will be validated and verified (see Data Validation below). Raw products that represent observations in instrument units (DN) will be calibrated, which converts them into physical units. The SDC will store all products on hard disk and distribute them to the Science Team and others via the WWW, or via alternate protocols where appropriate.

Additional inputs to the SDC include calibration files and procedures from the Spacecraft Instrument teams, ephemerides and other SPICE files from JPL/NAIF,

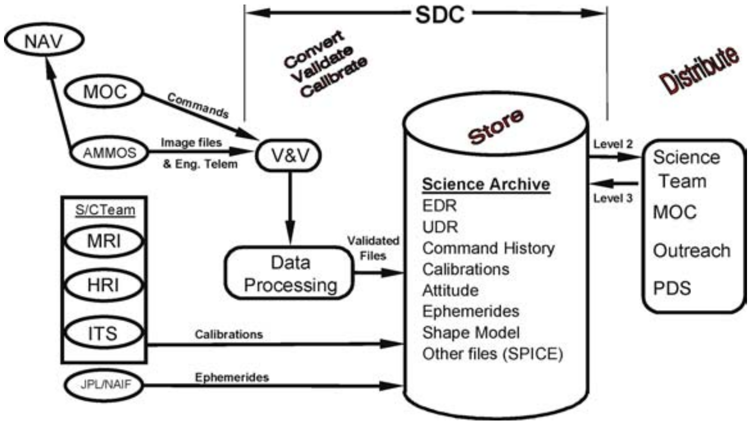

Figure 3. SDC Data Flow.

engineering telemetry from the spacecraft attitude control system (ACS), and products from the Science Team derived from the calibrated data and typically collapsible to a publication figure. Some of these additional inputs will become the basis for part of the pipeline, e.g., calibration files and procedures.

6.7. Standard Products

SDC products come from several sources: Products from the instrument pipeline described above, ephemerides from JPL/NAIF, engineering telemetry from the ACS, and composite products from the Science Team (e.g., mosaics, shape models).

Instrument data, both images and spectra, will be available in both raw (DN) and calibrated (physical) units. Calibrated data may be available in either Intensity/Flux ratio or Radiance units, or both.

The images and spectra will be files in the Flexible Image Transport System (FITS) format, a standard data format used in astronomy (see http://fits.gsfc.nasa.gov for details). The FITS format combines each observation with header information in a single file. The header information is flexible and expandable; at a minimum, it contains a description of the observation's data. The SDC, at the direction of the Science Team, will also place mission- and observation-specific information in the header to aid in science analysis and archiving. The raw data headers will contain the information available in the raw spacecraft files such as epoch of the observation, instrument identification, state (e.g., temperatures in DN units, filters used), and parameter settings (e.g., exposure duration, gain states). The calibrated data headers will combine the header information from the raw data with external information such as ephemerides, attitude information, and calibrations to expand the headers to include temperatures in physical units, observational geometry, calibration files used, software versions used to generate the files, etc.

The product headers will also be used as the basis of the Data Library and Catalog described below.

Ephemerides in the form of SPICE kernel files from JPL/NAIF are not products of the SDC, but they will be stored on the SDC and distributed to clients of the SDC. Engineering telemetry from the ACS will be converted to SPICE C-kernel files and used in the calibration pipeline. They will also be distributed to clients of the SDC.

Members of the Science Team will provide composite products such as mosaics and shape models of Tempel 1 to the SDC in the form of data files. The format will typically be FITS format, but may be negotiated with the Science Team as necessary. The main function of the SDC for these files is as a central collection point for eventual archiving.

6.8. Data Validation

Most of the data validation and verification will take place when the AMMOS at JPL decommutates telemetry packets to re-create the spacecraft files. The result of that validation will be at most a single Data Quality Index (DQI) value in the FITS header of the data file. The purpose of the DQI is to alert science users to the possibility of corrupted data. As the data go through the SDC pipeline, there will be further verification to ascertain the original command sequence that created each observation. Once that is known, it will be placed in the FITS header and be available in the Data Library and Catalog (see below). The Data Library and Catalog may then be used for further verification, e.g., to look for missing data files. This will also allow SDC clients to locate data using the original purpose of each sequence as a search key.

6.9. Data Library and Catalog – Overview

The workings behind two of the user interfaces, described functionally in the section SDC description – Interfaces above, will be described in more detail here.

The computer systems that make up the SDC keep track of observations by filename, but cryptic filenames such as dnivcaxf_20031013t22040001.fit are not much use to science team members and other clients of the SDC. As noted above, each observation, as a FITS file, has a header with mission- and observation-specific information. The catalog supports an interface for users of the SDC to search for, select, and retrieve observations based on the information in the FITS headers. To accomplish this, the SDC performs two tasks: convert the observational data into a database and provide a user-friendly interface to that database. Figure 4 summarizes these two tasks as connections between the data and the database and between the SDC user and the database. The next section details the pieces of the entire process.

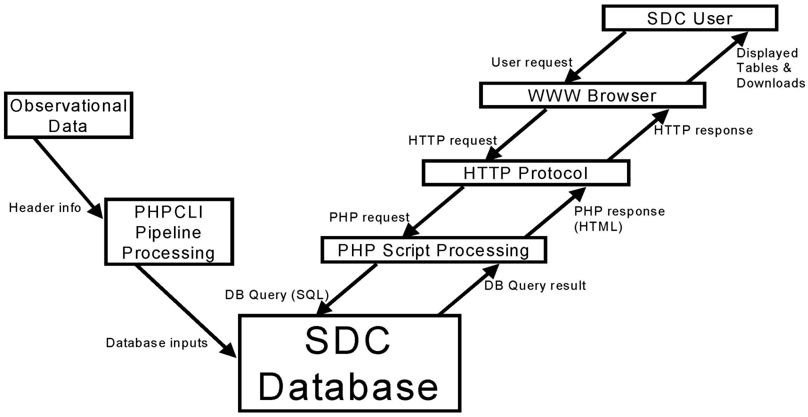

Figure 4. SDC User Interface Construction.

6.10. Data Library and Catalog – Details

The starting point for building the SDC database is the information stored in the FITS headers. That information is organized as keyword/value pairs as shown in Table XIX.

TABLE XIX
Subset of FITS header.

BITPIX =	16	/ 16-bit signed integer per data pixel
NAXIS =	2	/ Number of data axes
NAXIS1 =	1024	/Number of positions along axis 1
NAXIS2 =	1024	/Number of positions along axis 2
MISSION = 'DEEP IMPACT'		/ Name of the spacecraft mission
MSNPHASE = 'Encounter'		/ Phase of the spacecraft mission
EXPERMNT = 'LIGHT CURVE'		/ Experiment type
ORIGIN = 'CORNELL'		/ Institution that originated this file
BUNIT = 'DATA NUMBER'		/ Physical units for data pixel
OBSERVAT = 'IMPACTOR'		/ Observing platform (flyby or impactor)
INSTRUME = 'ITS'		/ Instrument (HRI/MRI/ITS)
DETECTOR = 'VISUAL CCD'		/ Detector Type
OBJECT = '9P/TEMPEL 1'		/ Target Name
EXPID =	40	/ Exposure ID
INTTIME =	100	/ [msec] Total integration time
EXPTIME =	100	/ [msec] Exposure time
OBSDATE = '2003-163'		/ Date at start of observation
OBSTIME = '12:34:56.678'		/ Time at start of observation

TABLE XX
FITS headers' partial summary.

Observation	BITPIX	NAXIS1	NAXIS2	MSNPHASE	EXPERMNT
I030130_123117_827_A.FIT	16	1024	1024	Encounter	Lightcurve
I030130_132209_044_A.FIT	16	64	64	Encounter	Lightcurve
I030130_182853_344_A.FIT	16	1024	1024	Encounter	Lightcurve
I030130_205410_027_A.FIT	16	1024	1024	Encounter	Lightcurve

The leftmost one to eight characters on each record is the keyword. The set of keywords for each instrument is fixed for that instrument. To the right of each keyword is an "equals" sign that serves as the delimiter between the keyword and the value. The value follows the equals sign and may be numeric or text. Text values are delimited by single quotes. Everything to the right of the value is a comment, delimited by a "slash" character.

The first task of the catalog is to insert each instrument's keyword/value pairs into a database with the keywords as columns and each observation's values summarized as a single row in the table as shown in Table XX.

As each observation, bundled in a FITS file, enters the SDC, automated scripts extract the keyword/value pairs and insert them into the central database. Observations are afforded one line each, with one column per keyword/value pair. The scripts are written in PHP4. The database itself is composed of the MySQL package.

The second task of the catalog is to present the SDC user with one or more interfaces to search, review and download images that match user-specified criteria. Once the FITS headers have been inserted into the SDC database, the web-based interface can be dynamically generated through a straightforward application of standard tools and protocols (displayed on the right-hand side of Figure 4 above). Again, PHP scripts are the heart of the interface. The scripts relay user requests to the database, gather the requested information from the database response, and display the requested information as formatted web sites, viewable in any web browser. The interface is in a constant state of improvement through ongoing input from the Deep Impact Science Team.

7. The Data Archive

7.1. Data Products

Once science data files have been produced by the SDC, they will be transferred to the Principal Investigator team at the University of Maryland, where the content and format will be validated and the archive volumes will be prepared.

The DI archive will contain science data products from each of the instruments, instrument calibration data, command history data, navigation and ancillary data in the form of SPICE kernel files, software, and sufficient documentation of the data, software, and mission to enable scientists to understand and use the archive well into the future. To produce this archive, a number of steps need to be carried out, including design of the archive structure and contents, generation of the archive components and an archive interface control document (ICD), peer review with the PDS, and final packaging and delivery. The science data products form the core of the archive; a list of the expected data products from each of the instruments is given in Table XXI. The data set collections to be archived are expected to be several gigabytes (GB) in size. The archive will be on-line at the PDS Small Bodies Node (PDS-SBN), consistent with current PDS practice. Several copies of a hard

TABLE XXI
Data Products and Archive Components.

Archive component	Data type	Data volume (GB)
Imagers (HRIVIS, MRIVIS, ITS)	Raw images	66.7
	Calibrated images (pre- and post-flight)	
	Calibrations	
	Support data	
	Shape model	
Spectrometer (HRI-IR)	Raw spectra	20.13
	Calibrations	
	Calibrated spectra	
Radio Science	Trajectory estimates and supporting products, e.g., SPICE attitude files, used to determine the cumulative effect of comet dust particle impacts on the spacecraft	.05
Earth-based	Images (Lowell Obs, Mauna Kea Obs, etc.), Spectra	100
Supporting	Reprocessed data from IRAS, Images, photometry from 2000 apparition	5.02
MERGE	Shape models	.01
Ancillary	Mission history files, SPICE Kernels	.01
Software	Calibration Algorithms	.01
	Higher Level Software (as provided by Science team)	
Documentation		.05
Total archive		182 GB

media archive will also be produced for deep archive purposes, using compact disks (CD) or digital versatile disks (DVD).

7.2. Archive Structure

The DI archive will be broken down into data set collections – one for each instrument, one for data sets deriving from more than one instrument (the MERGE data set collection), and one for SPICE data. A typical volume will contain data from a specified time interval. The top-level directory of a volume will thus contain directories for each of the data set collections and directories for each of the additional components of the archive, as required by PDS. The MERGE data will be ordered by time first, then by instrument, and further divided by type of data, if relevant. Data types and volumes for each archive component and for the total archive are shown in Table XXI. PDS requires a number of documentation files for each archive volume. One is a readme.txt – a text file describing the contents of the volume. Also required is voldesc.cat – a catalog of all the files residing on the volume. Each of the sub-directories under the top-level directory also requires one or more files to document the contents of that directory. The details of these files are specified in the PDS Standards Reference (2002).

7.3. Safed Data

Packet data and some ancillary files will be assembled and placed on CD-R or DVD media for long-term safekeeping in the event problems are discovered with the formally archived higher-level data products. Copies of this safed data (and allied documentation) will be provided to the PI, the Cornell SDC, and the NAIF node of the PDS. These same data will be archived by the JPL InterPlanetary Network for a minimum of three years after end of mission.

7.4. Archive Preparation

Science data products will be generated in PDS−compatible formats. This approach requires that each data file (data table or image file) be in a format approved by PDS and be accompanied by a PDS "label", actually a detached descriptive header file describing formally the content and structure of the accompanying data file. Ancillary data describing the observing conditions and spacecraft state when science data were acquired will be extracted from the packet data and SPICE kernels and placed in these PDS labels.

Science data products also include an extensive Earth-based archive of Tempel 1 data that will be collected in both pre- and post-encounter phases.

Files documenting the archive components will be prepared by the parties generating the data. In general, all information necessary to interpret and use the data is to be included in the archive. Additionally, the source code of all software to be provided with the archive will be collected, documented, and included in the archive.

PDS standards call for the documentation of the mission, spacecraft, instruments, and data products with special files called "catalog objects." Since the catalog objects take the form of a template that must be filled out with prescribed information, they are often referred to as "templates" even when they are already filled out. The required templates are the "mission template" describing the Deep Impact mission as a whole, the "instrument host template" describing the spacecraft, one "instrument template" for each instrument, and one "data set template" for each data set. These templates are to contain much of the information necessary to document the archive, and should make it possible for scientists to make correct use of the data in the future when the mission personnel are not available to support them. The PDS-SBN will fill in portions of the catalog objects, requiring only text descriptions of the mission, spacecraft, instruments, and data sets from DI personnel.

Figure 5 illustrates the flow of data from the Distributed Object Manager (DOM) at JPL to the SDC at Cornell University and the building of the archive through the

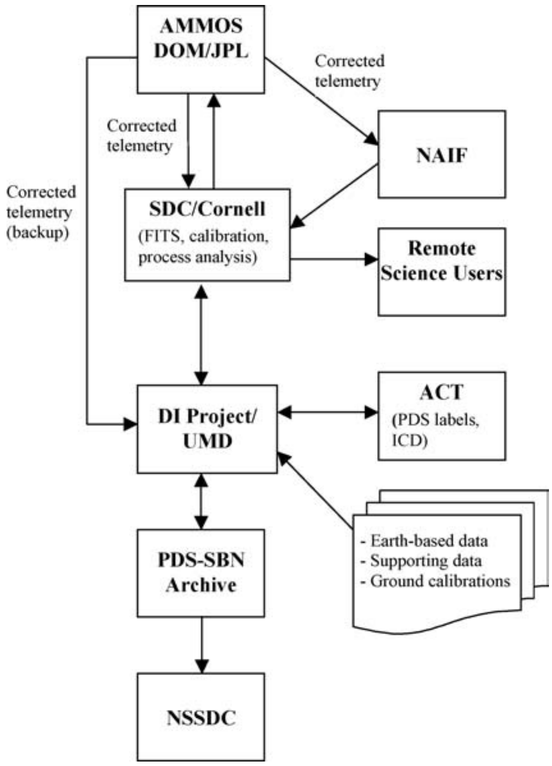

Figure 5. Building the Deep Impact archive.

TABLE XXII
Timeline for DI Project Archiving.

Delivery date	Archive Products
10/31/2003	IR model data (IRAS)
05/21/2004	Supporting data (Earth-based images, photometry from 2000 apparition)
07/2/2004	Ground calibration files
09/30/2004	Earth-based pre-encounter spectra and images
03/31/2005	Calibration files and payload tests during checkout
12/31/2005	Earth-based data leading up to impact. Spacecraft measurements through impact
03/31/2006	Earth-based post impact data

DI Project with its subcontractor, the Applied Coherent Technology (ACT), and the PDS Small Bodies Node at the University of Maryland.

7.5. Archive Validation

Data validation falls into two types, validation of the data itself and validation of the compliance of the archive with PDS archiving requirements. The first type of validation will be carried out by the Science Team, and the second will be overseen by the PDS-SBN, in coordination with the Science Team. The delivery schedule, with separate delivery dates for different portions of the mission (Table XXII), will facilitate validation by ensuring that problems in the early deliveries are resolved by the time of the later deliveries.

The formal validation of data content, adequacy of documentation, and adherence to PDS archiving standards is finalized with an external peer review. The peer review will be coordinated by the PDS-SBN. The peer review process may result in "liens" – actions recommended by the reviewers or by PDS-SBN personnel to correct the archive. All liens must be resolved by the data set provider: the SDC and PI team personnel for raw and calibrated data, the science team for higher-level data products and calibration algorithms. PDS will do a final validation prior to packaging and delivery.

7.6. Archive Packaging and Delivery

Data delivery will take place in stages, as specified in the timeline in Table XXII. Each delivery will be made to PDS via the appropriate medium. The final data delivery will incorporate the entire archive, including the earlier data deliveries.

7.7. Schedule for Archive Generation, Validation, and Delivery

The principal archive elements, namely the science data products defined in Table XXI, will be generated during the course of the mission, as will many ancillary products such as SPICE files. The general guideline for Discovery missions is that they deliver archive quality volumes to PDS at intervals not exceeding six months after receipt of the data used to make the products contained on the volume.

The planned timeline for archive delivery to PDS is shown in Table XXII. The final archive delivery is to be made 90 days after the end of the nominal mission in order to allow time for PDS review and lien resolution before the end of operations.

Following the delivery of archive volumes to PDS, the data will be peer reviewed by PDS over a several-month-long period. Any liens that are identified by the peer review process will be rectified by the Project and the appropriate science team members before they cease operation (expected to be 90 days after the end of mission for the science team). The DI project is responsible for resolving all liens against the final archive delivery. Final acceptance of the data by PDS will occur only after all liens have been cleared. The delivery of post-launch checkout data to the PDS will help to identify early in the mission any potential problems that can be addressed before the final archive is generated, thus avoiding liens on the data that require significant resources to correct.

There are no proprietary data rights for the DI Mission. We anticipate raw and calibrated, single-instrument data to be available six months after impact through the PDS-SBN. These data will be in the process of being peer-reviewed. We expect higher-level products, such as shape models, to be available about nine months after impact.

8. Summary

The planned DI observing sequence and ground processing of the returned data will result in a unique and comprehensive archival science data set that will permit researchers to begin to unlock some of the mysteries of those fascinating and spectacular solar system wanderers – comets.

Appendix: Abbreviations

ACS	Attitude control system
ACT	Applied coherent corporation
AMMOS	Advanced multimission operations system
CA	Closest approach
CCD	Charge-coupled device
CD	Compact disk
Dec	Declination
DI	Deep Impact

DN	Data number, digital (raw) instrument output
DOM	Distributed object manager
DQI	Data quality index
DSN	Deep space network
DVD	Digital versatile disk
FITS	Flexible image transport system
FOV	Field of view
Gb	Gigabits
GB	GigaByte (10^9)
HGA	High-gain antenna
HRI	High-resolution instrument
HRI-IR	High resolution instrument – infrared spectrometer
HRIVIS	High resolution instrument – VISible imager
HTTP	Hyper text transfer protocol
I	Impact
ICD	Interface control document
IDL	Interactive data language
IPN	Interplanetary network
IR	Infrared
IRAS	Infrared astronomical satellite
ITS	Impactor targeting sensor
JPL	Jet Propulsion Laboratory
L	Launch
MB	MegaByte (10^6)
MOC	Mission Operations Center
MRI	Medium resolution instrument
MySQL	"My" Structured Query Language
NAIF	Navigation Ancillary Information Facility
NAV	Navigation team
NSSDC	National Space Science Data Center
NVM	Non-volatile memory
PC	Personal computer
PDS	Planetary data system
PDS-SBN	Planetary data system-small bodies node
PHP	PHP: Hypertext Preprocessor
PHPCLI	PHP Command Line Interface
RA	Right ascension

R/T	Real time data return
S/C	Spacecraft
SBN	Small bodies node
SDC	Science Data Center
SM	Shield mode
SNR	Signal-to-noise ratio
SPICE	NAIF toolkit
SSH	Secure shell protocol
SSL	Secure sockets layer protocol
UDR	User data record
UMD	University of Maryland
VIS	Visible
V_{mag}	Visual magnitude
V&V	Validation and verification
WWW	World Wide Web

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